HEAT TREATMENT EFFECT ON THE CREEP OF INDUSTRIAL COPPER WIRE

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Abstract
Creep behavior of copper wire, produced by a wire drawing process, has been investigated by creep tests at 340°C under the stress 98,108 and 118 MPa. In this investigation, three samples have been tested: copper drawn wire non heat treated, and heat treated at 600°C and 700°C. Microstructure after the creep test was observed by optical microscopy to understand the rupture mechanism. We have found that the sample heat treated at 600 °C had a longer creep life. We have also deduced that the dislocation creep was the creep deformation mechanism of the drawn copper. SEM observations of fractured surfaces after creep tests of drawn copper wire non heat treated and treated 10 min at 600 °C under stress of 118 MPa.

Keywords: Creep, copper, heat treatment, rupture

1 Introduction
Copper has been one the most popular and important base metals for a long time, because of its excellent electric and thermal conductivity [1]. Copper wire is used in power generation, power transmission, power distribution, telecommunications, electronics circuitry, and countless types of electrical equipment.
However, the mechanical properties of copper such as creep resistance need more interests for industrial use. When the conductor is initially installed, it elongates following the initial curve that is not a straight line. Creep is the process by which viscoplastic flow occurs when a constant stress is applied to a metal for a prolonged period of time [2]. Creep resistance is an important attribute of high-temperature alloys, and mechanisms that control creep in alloys must be well understood by design of alloys that resist creep [3].
Creep can be determined by long-term laboratory creep tests, the results of which are used to generate creep curves. A creep behavior drop in pure copper and some copper alloys at high temperature has been reported by many researchers [4-8]. There are three basic mechanisms that can contribute to creep in metals, namely ; Dislocation slip and climb, Grain boundary sliding, and Diffusional flow. For example, Ayensu et al [4] have been studied creep mechanism of copper wires. They have been found that the creep mechanism is governed by grain boundary sliding. Boumerzoug et al [5], have been investigated creep mechanism of an industrial copper wire which were tested at temperature of 290 and 340°C under stresses of 98, 108 and 118 MPa. From activation energy values, they have found that the creep mechanism was climbing.
Generally, creep is dependent on the material, conductor construction, applied stress, the time and the temperature. However, in this present paper, this investigation was concerning the effect of

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the heat treatment at 600 and 700°C on the creep mechanism and creep resistance of an industrial copper wire.

2 Experimental Material and Techniques

The material used in this investigation is an industrial copper electric wire of composition 99.9 Cu, 0.001 Bi, 0.002 Sb, 0.002 As, 0.005 Fe, 0.002 Fe, 0.002 Ni, 005 Pb, 0.002 Sn, 0.004S, 0.004 Zn and 0.073 others elements. This material has been submitted to series of the wire drawing process at ENICAB (EntrepriseNationaled'Industrie de Cablerie) of Biskra. This copper wire is used in power transmission and distribution. Creep experiments were conducted in a creep test machine (Figure 1) using samples having gauge length of 100 mm and diameter of 2.4 mm. The creep specimens were tested at temperature 340 ° C and a stress of 98, 108 and 118 MPa. We have tested three samples: copper drawn wire non heat treated, and drawn wire heat treated at 600°C and at 700°C. All of the tests were continued until fracture occurred. Optical microscopy has conducted on wire after creep rupture.

In order to determine the yield stress of our material, the tensile test of the copper drawn wire was realized at room temperature with a strain rate of 0.1 mm/s on the testing machine ZWICK100kN. Samples had gauge length 20 mm and a diameter section of 2.4 mm. The obtained yield stress of copper drawn wire was 387 MPa. We notice that Frost and Ashby [9] are plotted the deformation mechanisms maps (Ashby maps) for various pure metals, using the stress values at 25° C. For that reason, we have chosen the stress values during all creep tests below the yield stress.

3 Results and Discussion

3.1 Creep tests

Results of creep test at temperature 340° C and under stress of 98,108 and 118 MPa of copper wire (non heat treated and heat treated at 600 and 700° C) are presented successively in **Figs. 1-3**. First of all, it appears from the obtained diagrams that all creep curves have a shape characteristic of the accelerated creep stage. However, from a given test stress, the shape of creep curves depends significantly on the temperature of the heat treatments. For example, at lower stress (98 MPa) (**Fig. 1**), copper wire heat treated at 600° C presented a slower deformation rate. At a higher test

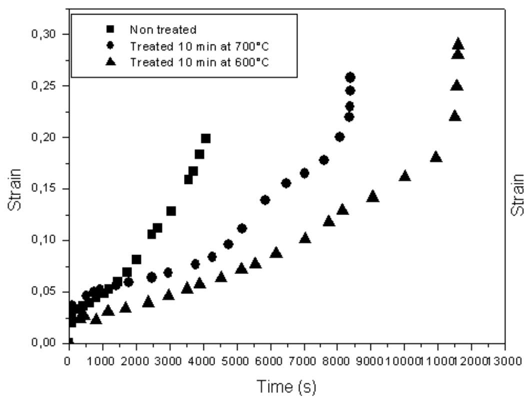

Fig. 1 Creep curves of drawn copper at 340 ° C under stress 98 MPa

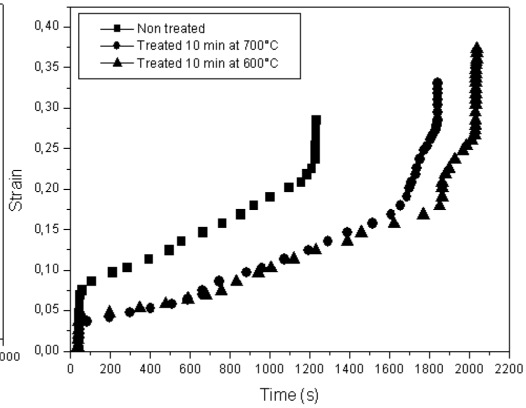

Fig. 2 Creep curves of drawn copper at 340 ° C under stress 108 MPa

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stress, 108 and 118 MPa (**Fig. 2** and **3**), a similar diversity of results concerning the creep resistance was obtained, where specimen heat treated at 600° C has a higher creep life. According to some previous results [10-13], this phenomenon might be caused by the effect of grain size, because, by increasing the temperature of heat treatment from 600°C to 700 °C, the grain size increases (**Fig. 4**). Wilshire and Palmer [10], have been studied the grain size effect on the strain rate during creep test of copper wire. They found that for low applied stresses, the strain rate increases by decreasing the grain size and the opposite result has been obtained for high applied stresses. For our case, the heat treated drawn copper at 700 °C which has a high grain size is characterized by a high strain rate and small lifetime during creep test (**Fig. 5**).

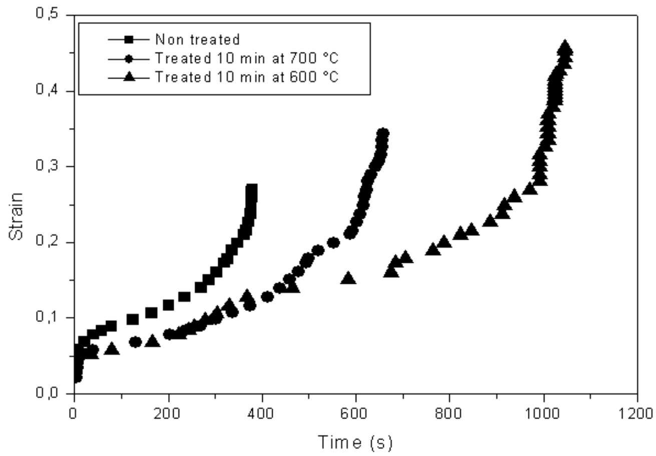

Fig. 3 Creep curves of drawn copper at 340 ° C under stress 118 MPa

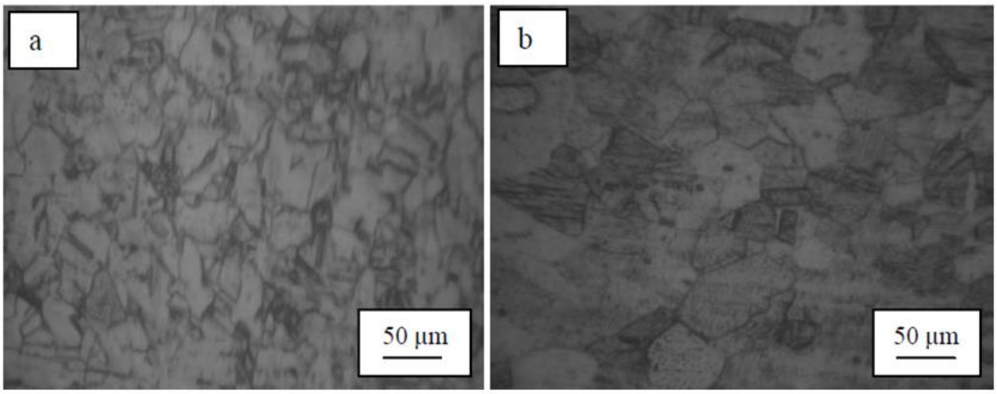

Fig. 4 Microstructures of drawn copper wires heat treated during 10 min at (a): 600 ° C and (b) 700 °

In order to compare our results to some previous studies, **Fig. 6** presents plotted curves of strain versus stress of our copper wires and other curves obtained in other investigations [5, 14-15]. These investigations confirm our results because our findings are close to these scientific works.

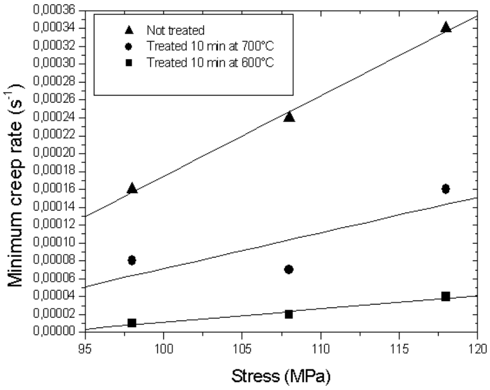

Fig. 5 Minimum creep rate plotted against applied stress

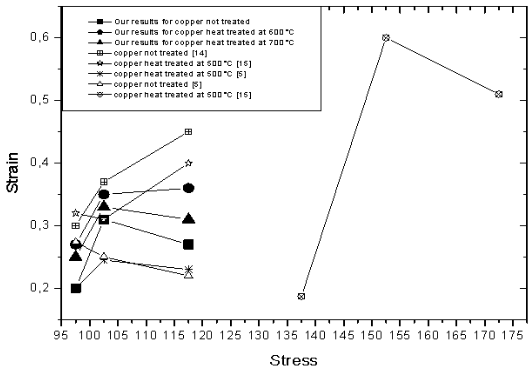

Fig. 6 Total strain in function of stress for various metals

3.2 Stress exponent analysis

The minimum creep rate generally varies with the applied stress through a power-law relationship (1) (Arrhenius relationship).

$$\dot{\varepsilon} = A\sigma^{n}\exp(-Q/RT) \qquad (1.)$$

Where ε^* minimum creep rate, σ stress, A the creep constant, R the gas constant, Q the activation energy and n the stress exponent. **Fig. 8** show versus for copper wires tested at 340 ° C (drawn copper wire non heat treated, and heat treated 10 min at 600 and 700°C). However, applying logarithms of both sides of equation (1), we obtain the simplified transformation:

$Log\,\dot{\varepsilon}$ versus $Log\,\sigma$

$$\log\dot{\varepsilon} = \log A + n\log\sigma - (Q/RT) \qquad (2.)$$

This equation is plotted in **Fig. 7**.

After taking the partial derivative of both sides of equation (2) with respect to log σ, the stress exponent *n* can be written as follows (3):

$$n = \left(\frac{\log\dot{\varepsilon}}{\log\sigma}\right)_T \qquad (3.)$$

Consequently, the value of n can be deduced from the plotted curves in **Fig. 7**. For example, for non heat treated drawn copper, the deformation mechanism is the dislocation creep since the value of n is 4. This n value indicates the dominance of dislocation glide and climb as the rate-controlling deformation mechanism [16]. But for drawn copper wire which has been heat treated at 600 and 700° C, the obtained stress exponents are :n = 7,22 for drawn copper wire heat treated at 600° C and n = 6,11 for drawn copper wire heat treated at 700° C. These values imply the occurrence of power-law-breakdown [17].

It is necessary to mention that the type of the creep mechanism is deduced from the value of the parameter n, if n is approximately equal to 1, the mechanism is diffusion creep, but if n is superior to 4, the mechanism is called the dislocation creep [2, 10]. Most of the researchers have found that

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n is superior to 4, which corresponds to the dislocation creep mechanism [8, 18-19]. For example Zikry and Georgy [8] have studied the creep behavior of the pure copper wire at temperature between 200 ° C and 400 ° C under stress from 87 MPa to 175 MPa. They found that the value of *n* is equal to 4 which they attributed the mechanism to the dislocation creep. The investigation of the creep behavior of aluminum alloy A 8090 by Wilshire and Scharning [18] they found that *n* was equal to 5 and they deduced that the mechanism corresponds to the dislocation creep.

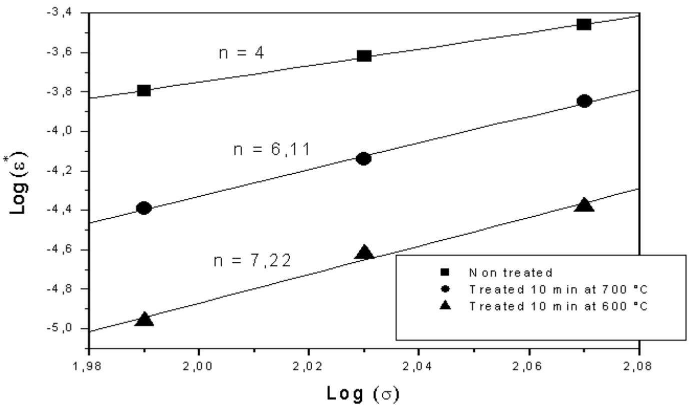

Fig. 7 . $Log\ \dot{\varepsilon}$ versus Log σ for copper wires tested at 340 ° C

3.3 Microstructure observations

The fracture surface for samples subjected to analysis by a scanning electron microscope. For example, from the macrographic observations after creep tests of drawn wire heat treated at 600°C for 10 min the shape of rupture region has lowest diameter in comparison to the other region of the sample, because the heat treatment increases the ductility of the material (**Fig. 8-b**). But in the sample non heat treated (**Fig. 8-a**), the variation of the section was very small relatively with sample treated. Micrographic observation after creep test of this heat treated drawn copper (**Fig. 8-c**) shows formation of voids with different size (5-50 μm). These voids correspond to the ductile fracture. It has been reported that ductile fracture is characterized by dimple morphology as it is observed in Ni-Cr steel by Dlouhy and Strnadel [20]. These cavities nucleated on the grain boundaries at first, they grew and chained together during deformation [21].

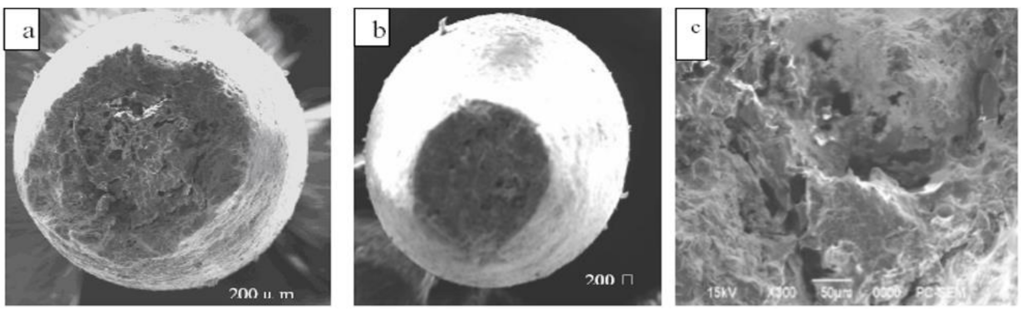

Fig. 8 SEM observations of fractured surfaces after creep tests of drawn copper wire non heat treated (a) and treated 10 min at 600 ° C (b, c) (under stress of 118 MPa)

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4 Conclusion

The effect of heat treatments temperature on the creep behavior of an industrial drawn copper has been studied under constant stresses and temperatures. The main results can be summarized as:

- The creep life increases with the decrease of the heat treatment temperatures. From an industrial point of view, heat treatment of the copper wire does not require a high amount of energy.
- The dominance of the dislocation creep mechanism during creep tests.
- The rupture mechanism is ductile fracture which characterized by the dimple morphology which gives lifetime to the material. In addition, this result confirms its high ductility, i.e., it is easy to draw down to diameters with very close tolerances.

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